POLYMERIZATION CATALYST AND PROCESS

BACKGROUND OF THE INVENTION

1. Field of Invention The present invention relates to a process for the atom transfer polymerization of olefinically unsaturated monomers in which molecular weight control is achieved by the presence of certain transition metals, especially copper, and diimine complexes.

2. Description of Related Art

It is desirable to be able to produce high molecular weight polymers with a low molecular weight distribution by catalyzed addition polymerization, in particular of vinylic monomers. Hitherto, this has been achieved by polymerizing via ionic processes typically in the presence of organometallics such as alkyl lithiums that are sensitive when reacted with water and other protic species. Therefore, monomers containing functional groups are not readily polymerized. The use of ionic systems also precludes the use of solvents that contain protic groups and/or impurities resulting in very stringent reaction conditions and reagent purity being employed.

More recently, radical polymerization systems based on the combination of a transition metal halide and an alkyl halide have been used. For example, Matyjasewski (Macromolecules (1995), vol. 28, pages 7901-7910 and WO96/30421) describes the use of CuX (where X=Cl, Br) in conjunction with bipyridine and an alkyl halide to give polymers of narrow

molecular weight distribution and controlled molecular weight. This system suffers from the disadvantage that the copper catalyst is only partially soluble in the system and thus a heterogeneous polymerization ensues. The level of catalyst that is active in solution is thus difficult to determine. Percec (Macromolecules, (1995), vol. 28, page 1995) has extended Matyjasewski's work by using arenesulphonyl chlorides to replace alkyl chlorides, again this results in heterogeneous polymerization. Sawamoto (Macromolecules, (1995), vol. 28, page 1721 and Macromolecules, (1997), vol. 30, page 2244) has also used a ruthenium based system for similar polymerization of methacrylates. This system requires activation of monomer by aluminum alkyl, itself sensitive to reaction with protic species which is an inherent disadvantage. These systems have been described as proceeding via a free radical mechanism that suffers from the problem that the rate of termination is > 0 due to normal radical-radical combination and disproportionation.

SUMMARY OF THE INVENTION

Surprisingly, the inventors of the present invention have found that the use of diimines such as 1,4-diaza-1,3-butadienes and 2-pyridinecarbaldehyde imines may be used in place of bipyridines. These ligands offer the advantage of homogeneous polymerization and thus the level of active catalyst can be accurately controlled. This class of ligand also

enables the control of the relative stability of the transition metal valencies, for example, Cu(I) and Cu(II), by altering ancillary substituents and thus gives control over the nature of the products through control over the appropriate chemical equilibrium. Such a system is tolerant to trace impurities, trace levels of O_2 and functional monomers, and may even be conducted in aqueous media.

A further advantage of the system of the present invention is that the presence of free-radical inhibitors traditionally used to inhibit polymerization of commercial monomers in storage, such as 2, 6-di-tert-butyl-4-methylphenol (topanol), increases the rate of reaction of the present invention. This means that lengthy purification of commercial monomers to remove such radical inhibitors is not required. Furthermore, this indicates that the system of the invention is not a free-radical process. This is contrary to the Matajaszewski and Sawamoto who show free-radical based systems.

Accordingly a first aspect of the invention provides a catalyst for addition polymerization of olefinically unsaturated monomers, especially vinylic monomers, comprising:

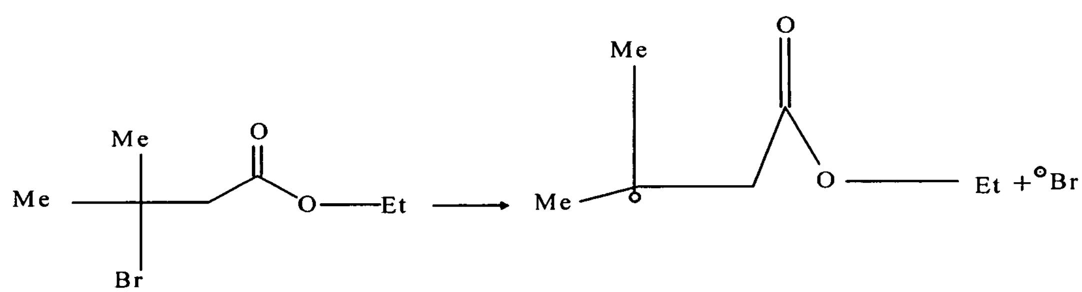
a) a first compound of formula 1

MY

where M is a transition metal in a low valency state or a transition metal in a low valency state coordinated to at least one coordinating non-charged ligand and Y is a monovalent or polyvalent counterion;

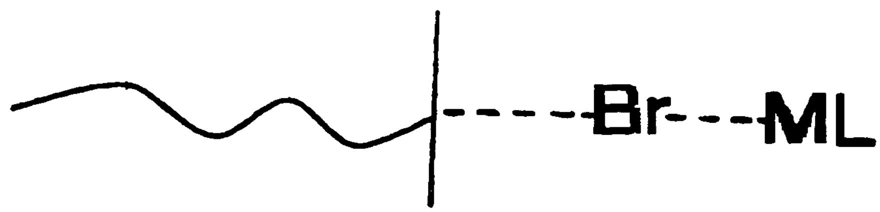
b) an initiator compound comprising a homolytically cleavable bond with a halogen atom.

A "homolytically cleavable bond" means a bond that breaks without integral charge formation on either atom by homolytic fission. Conventionally, this produces a radical on the compound and a halogen atom radical. For example:



However, the increase in the rate of reaction observed by the inventors with free-radical inhibitors indicates that true free-radicals do not appear to be formed using the catalysts of the present invention. It is believed that this occurs in a concerted fashion whereby the monomer is inserted into the bond without formation of a discrete free radical species in the system. That is, during propagation this results in the formation of a new

carbon-carbon bond and a new carbon-halogen bond without free-radical formation. The mechanism involves bridging halogen atoms such as:



where:

ML is a transition metal-diimine complex as defined below.

A "free-radical" is defined as an atom or group of atoms having an unpaired valence electron and which is a separate entity without other interactions.

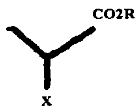
c) an organodiimine, where one of the nitrogens of the diimine is not part of an aromatic ring.

Transitional metals may have different valencies, for example Fe(II) and Fe(III), Cu(I) and Cu(II), a low valency state is the lower of the commonly occurring valencies, i.e. Fe(II) or Cu(I). Hence M in Formula I is preferably Cu(I), Fe(II), Co(II), Ru(II) or Ni(II), most preferably Cu(I). Preferably, the coordinating ligand is $(CH_3CN)_4$.Y may be chosen from Cl, Br, F, I, NO_3, PF_6, BF_4, SO_4, CN, SPh, SCN, SePh or triflate (CF_3SO_3). Copper (I) triflate may be in the form of a commercially available benzene complex $(CF_3SO_3Cu)_2C_6H_6$. The most preferred compound is CuBr.

Preferably, the second component (b) is selected from

RX

Formula 2



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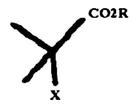

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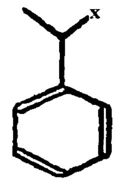

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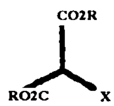

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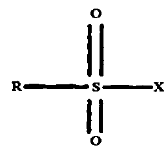

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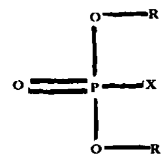

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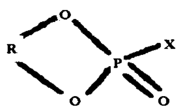

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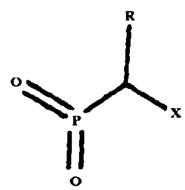

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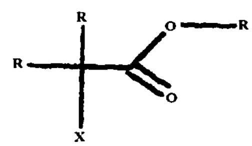
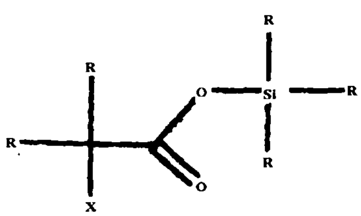


Formula 11

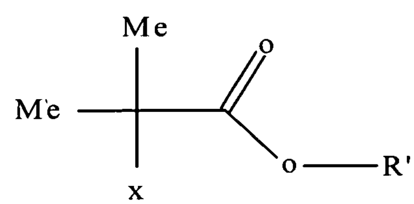


Formula 12

where R is independently selectable and is selected from straight, branched or cyclic alkyl, hydrogen, substituted alkyl, hydroxyalkyl, carboxyalkyl or substituted benzyl. Preferably the or each alkyl, hydroxyalkyl or carboxyalkyl contains 1 to 20, especially 1 to 5 carbon atoms.

X is a halide, especially I, Br, F or Cl.

The second component (b) may especially be selected from Formulae 13 to 23:



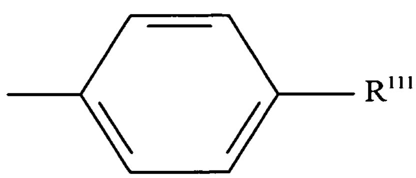
Formula 13

where:

X = Br, I or Cl, preferably Br

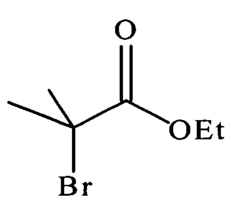
R' = -H,

$-(CH_2)_pR''$ (where m is a whole number, preferably p = 1 to 20, more preferably 1 to 10, most preferably 1 to 5, R'' = H, OH, COOH, halide, NH_2, SO_3, COX - where x is Br, I or C) or:



Formula 14

R^{111} = -COOH, -COX (where X is Br, I, F or Cl), -OH, $-NH_2$ or $-SO_3H$, especially 2-hydroxyethyl-2'-methyl-2' bromopropionate.



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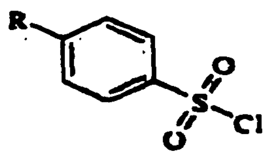
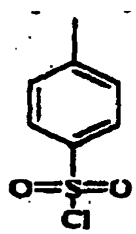


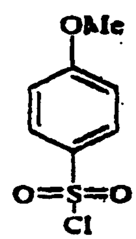
R = Me, MeO, halogen.

Formula 16

Especially preferred examples of Formula 16 are:

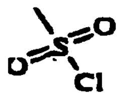


Formula 16A

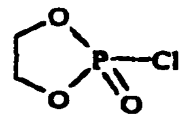


Formula 16B

Br may be used instead at Cl in Formulae 16A and 16B.



Formula 17



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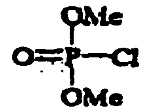

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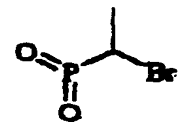
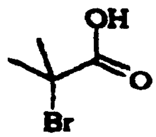


Formula 20



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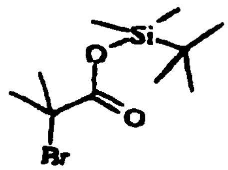
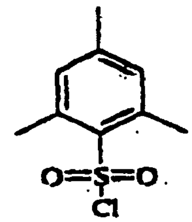


Formula 22

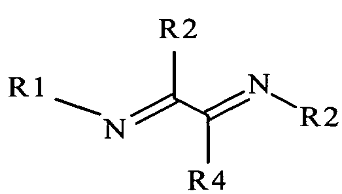
and



Formula 23

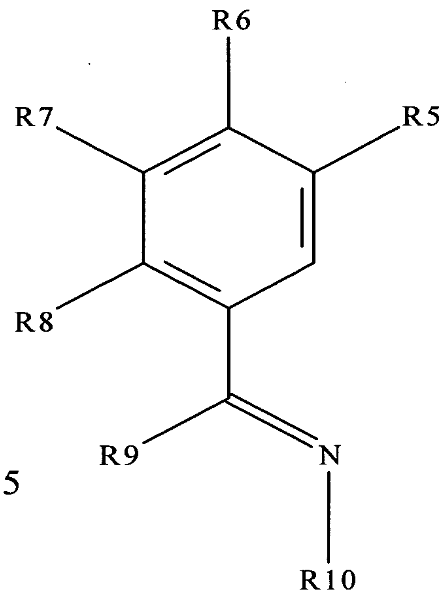
The careful selection of functional alkyl halides allows the production of terminally functionalized polymers. For example, the selection of a hydroxy containing alkyl bromide allows the production of α-hydroxy terminal polymers. This can be achieved without the need of protecting group chemistry.

Component (c) may be a 1,4-diaza-1,3-butadiene



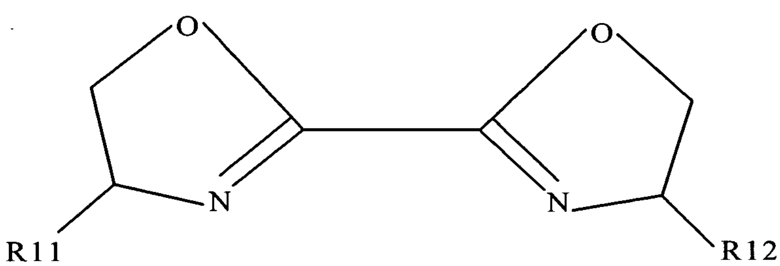
Formula 24

a 2-pyridinecarbaldehyde imine



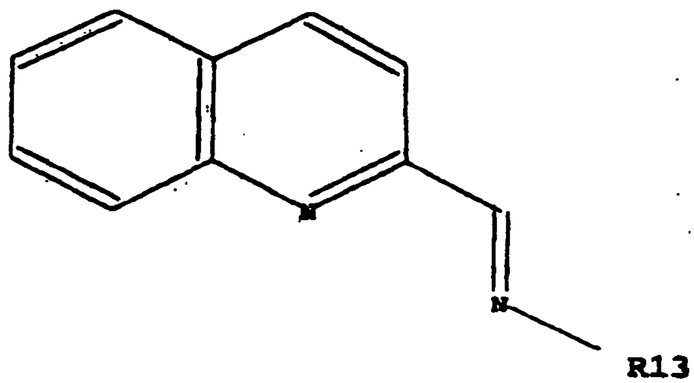
Formula 25

An Oxazolidone



Formula 26

or a Quinoline Carbaldehyde



Formula 27

where R_1, R_2, R_{10}, R_{11}, R_{12} and R_{13} may be varied independently and R_1, R_2, R_{10}, R_{11}, R_{12} and R_{13} may be H, straight chain, branched chain or cyclic saturated alkyl, hydroxyalkyl, carboxyalkyl, aryl (such as phenyl or phenyl substituted where substitution is as described for R_4 to R_9), CH_2Ar (where Ar = aryl or substituted aryl) or a halogen. Preferably R_1, R_2, R_{10}, R_{11}, R_{12} and R_{13} may be a C_1 to C_{20} alkyl, hydroxyalkyl or carboxyalkyl, in particular C_1 to C_4 alkyl, especially methyl or ethyl, n-propylisopropyl, n-butyl, sec-butyl, tert butyl, cyclohexyl, 2-ethylhexyl, octyl decyl or lauryl. R_1, R_2, R_{10}, R_{11}, R_{12} and R_{13} may especially be methyl.

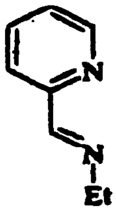
R_3 to R_9 may independently be selected from the group described for R_1, R_2, R_{10}, R_{11}, R_{12} and R_{13} or additionally OCH_{2n+1} (where n is an integer from 1 to 20), NO_2, CN or O=CR (where R = alkyl, benzyl $PhCH_2$ or a substituted benzyl, preferably a C_1 to C_{20} alkyl, especially a C_1 to C_4 alkyl).

Furthermore, the compounds may exhibit a chiral centre α to one of the nitrogen groups. This allows the possibility for polymers having different stereochemistry structures to be produced.

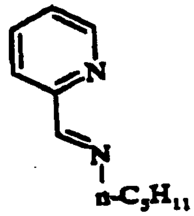
Compounds of general Formula 25 may comprise one or more fused rings on the pyridine group.

One or more adjacent R_1 and R_3, R_3 and R_4, R_4 and R_2, R_{10} and R_9, R_8 and R_9, R_8 and R_7, R_7 and R_6, R_6 and R_5 groups may be C_5 to C_8 cycloalkyl, cycloalkenyl, polycycloalkyl, polycycloalkenyl or cyclicaryl, such as cyclohexyl, cyclohexenyl or norborneyl.

Preferred ligands include:



Formula 28



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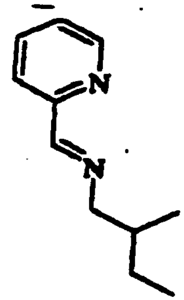

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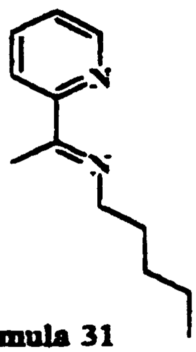

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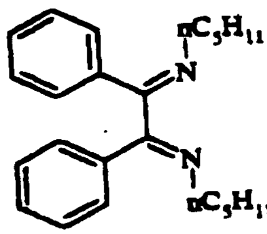

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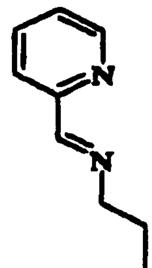

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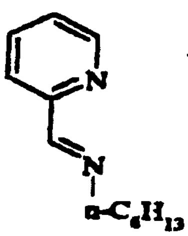

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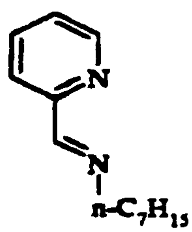

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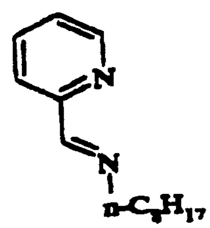

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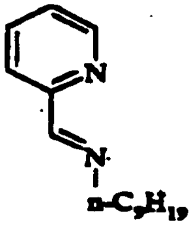

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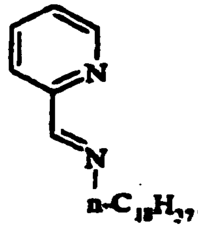

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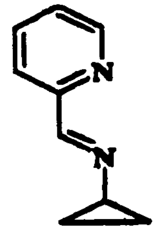

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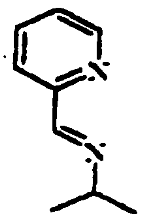

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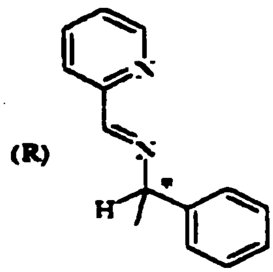

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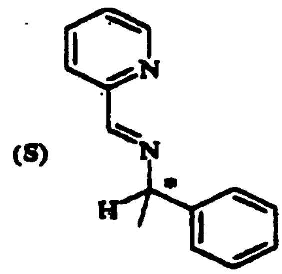

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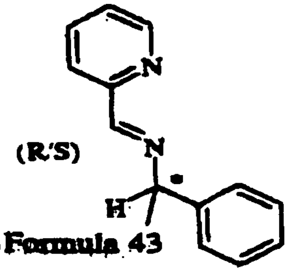

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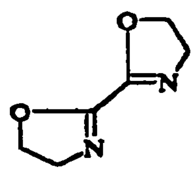

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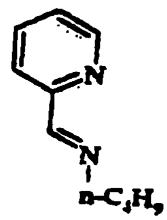

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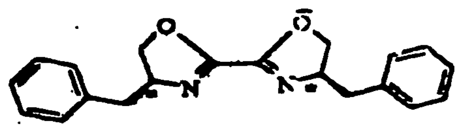

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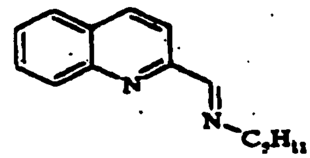

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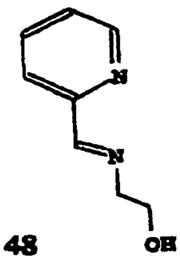

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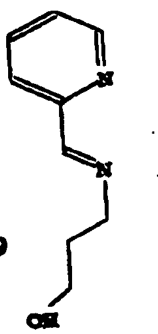

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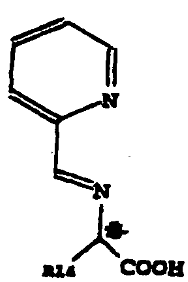
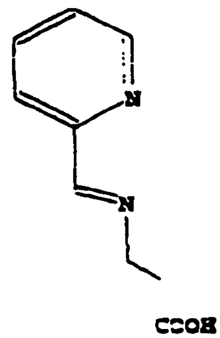


Formula 50

and



Formula 51

where: * indicates a chiral centre

R14 = Hydrogen, C_1 to C_{10} branched chain alkyl, carboxy- or hydroxy- C_1 to C_{10} alkyl.

A second aspect of the invention provides a catalyst for addition polymerization of olefinically unsaturated monomers, especially vinylic monomers, comprising:

a first component of Formula 51

$[ML_m]^{n+} A^-$

wherein M = a transitional metal in a low valency state;

L = an organodiimine, where at least one of the nitrogens of the diimine is not part of an aromatic ring,

A = an anion

n = a whole integer of 1 to 3

m = an integer of 1 to 2.

(e) An initiator comprising a homolytically cleavable bond with a halogen atom, as previously defined.

Preferably, M is as previously defined for component (a). L may be a compound according to Formula 24, 25, 26 or 27, as previously defined. A may be F, Cl, Br, I, NO_3, SO_4 or CuX_2 (where X is a halogen).

The preferred initiators (e) are as defined for the first aspect of the invention. The invention also provides the use of the catalyst according to the first or second aspect of the invention in the addition polymerization of one or more olefinically unsaturated monomers and the polymerized products of such processes.

The components (a), (b) and (c), or (d) and (e) may be used together in any order.

The inventors have unexpectedly found that the catalyst will work at a wide variety of temperatures, including room temperature and as low as -15°C. Accordingly, preferably the catalyst is used at a temperature of -20°C to 200°C, especially -20°C to 150°C, 20°C to 13°C, more preferably 90°C.

The olefinically unsaturated monomer may be a methacrylic, an acrylate, a styrene, methacrylonitrile or a diene such as butadiene.

Examples of olefinically unsaturated monomers that may be polymerized include methyl methacrylate, ethyl methacrylate, propyl methacrylate (all isomers), butyl methacrylate (all isomers), and other alkyl methacrylates; corresponding acrylates; also functionalized methacrylates and acrylates including glycidyl methacrylate, trimethoxysilyl propyl methacrylate, allyl methacrylate, hydroxyethyl methacrylate, hydroxypropyl methacrylate, dialkylaminoalkyl methacrylates; fluoroalkyl (meth)acrylates; methacrylic acid, acrylic acid; fumaric acid (and esters), itaconic acid (and esters), maleic anhydride; styrene, α-methyl styrene; vinyl halides such as vinyl chloride and vinyl fluoride; acrylonitrile, methacrylonitrile; vinylidene halides of formula $CH_2 = C(Hal)_2$ where each halogen is independently Cl or F; optionally substituted butadienes of the formula $CH_2 = C(R_{15})\ C(R_{15}) = CH_2$ where R_{15} is independently H, C1 to C10 alkyl, Cl, or F; sulphonic acids or derivatives thereof of formula $CH_2 = CHSO_2OM$ wherein M is Na, K, Li, $N(R_{16})_4$ where each R_{16} is independently H or C1 or V10 alkyl, D is COZ, ON, $N(R_{16})_2$ or SO_2OZ and Z is H, Li, Na, K or $N(R_{16})_4$; acrylamide or derivatives thereof of formula $CH_2 = CHCON(R_{16})_2$ and methacrylamide or derivative thereof of formula $CH_2 = C(CH_3)CON(R_{16})_2$. Mixtures of such monomers may be used.

Preferably, the monomers are commercially available and may comprise a free-radial inhibitor such as 2, 6-di-tert-butyl-4-methylphenol or methoxyplenol.

Preferably, the co-catalysts are used in the ratios (c):(a) 0.01 to 1000, preferably 0.1 to 10, and (a):(b) 0.0001 to 1000, preferably 0.1 to 10, where the degree of polymerization is controlled by the ratio of monomer to (b).

Preferably, the components of the catalyst of the second aspect of the invention are added at a ratio M:initiator of 3:1 to 1:100.

Preferably, the amount of diimine : metal used in the systems is between 100:1 and 1:1, preferably 5:1 to 1:1, more preferably 3:1 to 1:1.

The reaction may take place with or without the presence of a solvent. Suitable solvents in which the catalyst, monomer and polymer product are sufficiently soluble for reactions to occur include water, protic and non-protic solvents including propionitrile, hexane, heptane, dimethoxyethane, diethoxyethane, tetrahydrofuran, ethylacetate, diethylether, N,N-dimethylformamide, anisole, acetonitrile, diphenylether, methylisobutyrate, butan-2-one, toluene and xylene. Especially preferred solvents are xylene and toluene, preferably the solvents are used at at least 1% by weight, more preferably at at least 10% by weight.

Preferably, the concentration of monomer in the solvents is 100% to 1%, preferably 100% to 5%.

The reaction may be undertaken under an inert atmosphere such as nitrogen or argon.

The reaction may be carried out in suspension, emulsion, mini-emulsion or in a dispersion.

Statistical copolymers may be produced using the catalysts according to the present invention. Such copolymers may use 2 or more monomers in a range of about 0-100% by weight of each of the monomers used.

Block copolymers may also be prepared by sequential addition of monomers to the reaction catalyst.

Telechelic polymers, may be produced using catalysts of the invention. For example, a functional initiator such as Formula 21 may be used with transformation of the ωBr group to a functional group such as -OH or

$-CO_2H$ via use of a suitable reactant such as sodium azide.

Comb and graft copolymers may be produced using the catalysts of the invention to allow, for example, polymers having functional side chains to be produced, by use of suitable reagents.

<u>BRIEF DESCRIPTION OF THE DRAWINGS</u>

Embodiments of the invention will now be described by way of example and with reference to the following figures:

Fig. 1 shows the structure of the ligand 2,6 dimethylanilineDAB;

Fig. 2 shows the crystal structure of the cation obtained by reacting tBuDAB and CuBr together;

Figs. 3 and 4 show Mn dependence on conversion of different monomer initiator ratios for styrene and methylmethacrylate respectively;

Fig. 5 shows Mw/Mn dependence on conversion for bulk polymerization of styrene at 80°C;

Fig. 6 shows kinetic plots for polymerization of methylmethacrylate at 90°C;

Fig. 7 shows the reaction scheme for the production of hydroxy terminally functionalized PMMA. (i) Br_2-P, (ii) Ethylene glycol, (iii) CuBr/3/MMA, (iv) benzoyl chloride;

Fig. 8 shows a selected region from 'H NMR spectra of (a) 3, (b) 4 CH_2-O-groups and -OCH_3 • to Br and aromatic protons from benzoyl group;

Fig. 9 shows partial MALDI-TOF-MS of 3 between x = 8 and 11, peaks correspond to lithium adducts of molecular ions with no observable fragmentation;

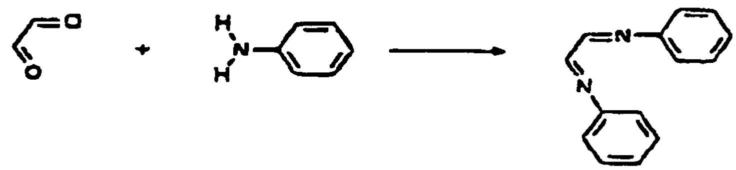
Fig. 10 shows a plot showing how Mn from SEC increases with conversion for experiments D-K.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Examples

Synthesis of Ligands

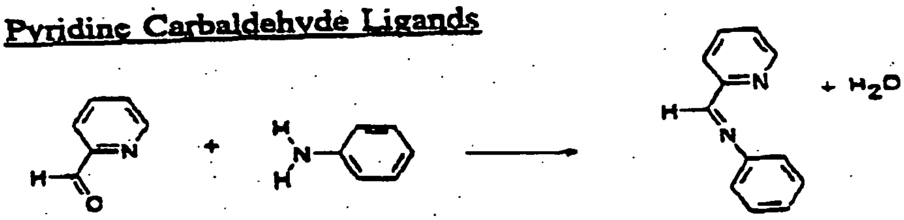
Diazabutadiene (DAB) Ligands



Glyoxal **Aniline (phenylamine)** **Dimethylaniline DAB**

To a stirred solution of 40% aqueous glyoxal (0.25 mol) in a conical flask was added the required amine dropwise (0.5 mol). After a period of time a pale yellow solution formed which was taken up with water and filtered. The resulting precipitate was dissolved in diethyl ether and poured over a large excess of magnesium sulfate. The solution was left for twelve hours to remove all the water and the solution was filtered. Ether was removed on a rotary evaporator then the product recrystallized from ether. TertButyl DAB (tBu DAB) and isoPropyl DAB (iPr DAB) were similarly manufactured using t-butylamine and isopropylamine respectively as the starting amine. Such compounds are superior to 2,2-bipyridine in accepting electron density

Pyridine Carbaldehyde Ligands



2-pyridinecarb-aldehyde　　aniline　　aniline PCA

To a stirred solution of pyridine carbaldehyde in ether was added an equimolar quantity of amine. The solution was left for 3 hours then poured over an excess of magnesium sulfate. The solution was filtered and the ether removed on a rotary evaporator. Some ligands formed yellow oils and were purified by distillation under reduced pressure. Solids were purified by recrystallization from ether.

tBu PCA, iPr PCA, nButyl PCA (nBu PCA), Dimethylaniline PCA, Diisopropylaniline PCA and methoxyaniline PCA were also made by reacting $^{t}BuNH_2$, $^{i}PrNH_2$, $^{n}BuNH_2$, 2,6-dimethylaniline, 2,6-diisoproxylaniline and 4-methoxyaniline, respectively as the amine.

Characterization of Ligands

Ligands have been initially characterized by NMR and EI/CI mass spectrometry. Mass spec data is tabulated below.

DIAZABUTIENE (DAB) LIGANDS

Structure	RMM	M/Z
tBu DAB	168	166
iPr DAB	140	141
Dimethylaniline DAB	262	249

PYRIDINE CARBALDEHYDE **(PCA) LIGANDS**

Structure	RMM	M/Z
tBu PCA	162	163
iPr PCA	149	149
nBu PCA	162	163
Aniline PCA	182	182
Dimethylaniline PCA	212	209
Diisopropylaniline PCA	268	223
Methoxyaniline PCA	197	211

A crystal structure has been obtained of the ligand 2, 6 dimethylaniline DAB (Fig. 1). This shows a E configuration of double bonds which must fold around the metal centre to form the catalyst.

Synthesis of Catalysts

To a solution of ligand (in acetone) in a schlenk ways added copper bromide , chloride or $Cu(CH_3CN)_4BF_4$ under nitrogen. The solution was filtered by cannular and placed in a freezer. Solvent was removed by filtration and the crystals examined by FAB mass spectrometry. Catalysts were synthesised with equimolar quantities of ligand and anion or excess ligand (2:1). Both experiments resulted in the detection of a peak corresponding to CuL2.

L = ligand.

Ligand	Ligand : anion	Anion	Mass spectrometry data M/Z			
			CuL	CuL_2	Cu_2L_2Cl	$Cu_3L_2Cl_2$
tBuDAB	1:1	Br	231	399		
tBuDAB	1:1	BF_4	231	399		
tBuDAB	2:1	Br	231	399		
tBuDAB	1:1	Cl	-	399	499	597
iPrDAB	1:1	Br	203	343		
tBuPCA	1:1	Br	225	387		
tBuPCA	1:1	BF_4	225	387		
tBuPCA	1:1	Cl	-	387		
Bipy	1:1	Br	300	456		
Bipy	1:1	BF_4	219	375		
Bipy	2:1	BF_4	219	375		
Bipy	1:1	Cl	-	375		

Bipy (Bipyridyl) is included as a comparison.

A crystal structure has been obtained for the reaction of tBu DAB and CuBr indicating a tetrahedral intermediate (Fig. 2).

Polymer Synthesis

The catalysts were used to control the propagation of styrene and methylmethacrylate.

All polymerizations were performed with excess ligand [L]:[Cu] 3:1 and the catalyst is synthesized in situ.

General method for polymerization of methylmethacrylate

To a Schlenk flask to be purged with nitrogen was added 0.54 mls ethyl 2-bromo-isobutyrate (0.00372 mols) in 10 mls methylmethacrylate (0.0935 mols). The desired ligand was then added (0.01122 mols) and the entire solution was freeze pump thaw degassed. 0.536g copper bromide (0.00374 mols) was then added whilst stirring. When the solution turned deep red indicating formulation of the catalyst the Schlenk flask was immersed in an oil bath at 90°C.

Polymerization results

All polymerisations are based on the following mole ratios.

Monomer : Initiator : Copper X · Ligand
100 · 1 : 1 : 3

Copper X = catalyst based on copper.

Styrene (Sty) was initiated with 1-phenylethyl bromide or chlorine.

Methylmethacrylate (MMA) was initiated with ethyl-2-bromo isobutyrate.

ligand	mon.	X	t/hrs	T/°C	Mn	Mw	PDI	Conv%
tBuDAB	STY	Br	24	110	2,173	4,438	2	11
iPrDAB	STY	Br	24	110	1,975	72,587	38	5
dimethylanilineDAB	STY	Br	24	110	467	4,156	9	80
tBuPCA	STY	Br	24	110	338	1,110	3.2	1
anilinePCA	STY	Br	24	110	6,458	22,376	3.5	41
dimethylaniline	STY	Br	24	110	3,017	9,167	3	68
tBuPCA	STY	Cl	20	130	42,551	102,776	2.45	20
nBuPCA	STY	Cl	3	130	6,951	22,571	3.25	40
iPrPCA	STY	Cl	20	130	15,607	41,125	2.64	33
anilinePCA	STY	Br	20	110	6,458	22,376	4	41
dimethylanilinePCA	STY	Br	20	110	3,017	9,167	3	68
ipropylanilinePCA	STY	Br	20	130	3,700	10,074	2.72	61
methoxyanilinePCA	STY	Br	20	130	9,723	24,772	2.5	69
anilinePCA	MMA	Br	18	110	477	4,600	9.6	2
dimethylanilinePCA	MMA	Br	18	110	6,293	12,210	1.94	68
nBuPCA	MMA	Br	4	100	10,251	12,273	1.2	95
nBuPCA	MMA	Br	1	130	7,376	12,422	1.68	-
nBuPCA	STY	Br	40	80	5,492	7,313	1.33	43
nBuPCA	STY	Br	20	80	6,343	9,533	1.5	39

Polymerization with tBuDAB

t-BuDAB was also investigated in more detail using different ratios of Ligand (L), Initiator (I) and catalyst (Cu).

Styrene at 100°C

L:I	Cu:I	Mn	PDI	%Conv.
3	1	2173	2.0	11
3	20	2603	4.0	7
3	100	2169	5.8	8
1	1	2400	3.6	9
1	100	8042	14	7

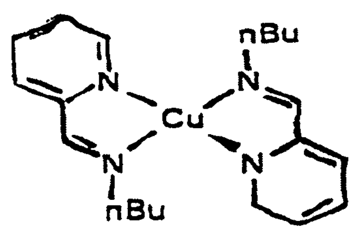
MMA (100°C)

3	1	2020	4.1	Low

This shows that PDI may be controlled by varying the ratio of L:I and/or Cu:I.

Polymerizations with nBuPCA

A successful ligand was nBuPCA which will form the following copper (I) structure:



This catalyst has been used to obtain kinetic data for the polymerization of both styrene and methylmethacrylate. Temperature control is important to prevent termination leading to tailing of the resulting MW distribution. If termination is prevented then polydispersity will decrease with time. Mn conversion plots have been obtained at different monomer to initiator ratios.

Figs. 3 and 4 show Mn dependence on conversion at different monomer:initiator for styrene and methylmethacrylate at 80°C.

Fig. 5 shows Mw/Mn dependence on conversion for bulk polymerization of styrene at 80°C.

Fig. 6 shows kinetic plots for the polymerization of methylmethacrylate at 90°C.

<u>Synthesis of Block Co-polymers</u>

This was investigated using methylmethacrylate, benzylmethacrylate (BzMA) and 2 hydroxyethylmethacrylate (HEMA) the results of which are shown in the table below:

TABLE B

BLOCK ONE				BLOCK TWO				
Mon.	Mn	Mw	PDi	Mon.	Mn	Mw	PDi	% MMA
MMA	2,469	2,965	1.2	MMA	5,599	7,337	1.31	100
MMA	2,469	2,965	1.2	BzMA	4,908	6,500	1.32	70
MMA	2,499	3,431	1.37	BzMA	5,934	10,749	1.81	54
MMA	2,499	3,431	1.37	HEMA	3,298	5,544	1.68	70

Statistical Copolymers

An example of a statistical copolymer was produced using a compound of Formula 16B as initiator and a compound of Formula 45 as the ligand.

1g of 2-hydroxyethyl methacrylate with 9.36g of MMA (I. e. 7.7. mole%) was polymerized with the following results:

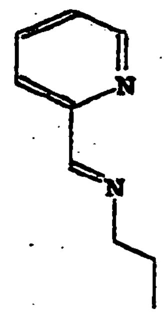
Initiator	Ligand	Amount ligand/ mL	Solvent (conc wt%)	Amt. CuBr/g	Amt. Initiator /g	Temp. °C	Time mins.
16B	45	0.37	33.3	0.13	0.16	90	2,760

Results:

Mn	PDI	% HEMA (NMR)
14,764	1.21	4.5

Further experimentation

Further experimentation was also carried out using ligands of Formula 33.



Formula 33

This was synthesized as follows:

30mls of diethylether was placed in a conical flask. 1.78mls of 2-pyridine carbaldehyde (2.00g, 1.867 x 10^{-2} moles) were added prior to 1.54mls or propylamine (1.11g, 1.873 x 10^{-2} moles). The reaction mixture immediately turns yellow. The mixture was stored for 10 minutes at room temperature prior to the addition of magnesium sulfate and stirring for a further 30 minutes. The reaction mixture was filtered and the volatiles removed under reduced pressure. The product is isolated as a yellow oil.

Polymerization

0.688g of copper (I) bromide (98% Aldrich)(4.796×10^{-4} moles) were added to 10 mls of methylmethacrylate purified by passage down a column containing basic alumina and 3A sieves under nitrogen (9.349×10^{-2} moles) in 20 mls of xylene (deoxygenated by 3 freeze-pump-thaw cycles and dried over 3A sieves for 12 hours). 0.2136g of A (1.44×10^{-3} moles) were added over 2 minutes with stirring at room temperature to give a homogenous deep red/brown solution. 0.07mls of ethyl 2-bromoisobutyrate (0.0924g, 4.73×10^{-4} moles) were added and the reaction mixture heated to 90°C for 485 minutes. Samples were taken at intervals and analyzed for Mn and conversion, see table. After 485 minutes poly(methylmethacrylate) was isolated by precipitation into methanol in 78.6% yield with Mn = 7020 and PDI (Mw/Mn) = 1.27.

TIME	% CONVERSION	Mn	PDI
120	16.47	2376	1.28
240	52.69	5249	1.22
300	61.02	6232	1.18
360	67.56	6742	1.21
485	78.56	7020	1.27

The Production of α-hydroxy terminally functionalized PMMA

The initiator, ethyl-2-bromoisobutyrate was replaced with hydroxy containing alkyl bromide so as to produce •-hydroxy terminally functionalized PMMA without the need to employ protecting group chemistry.

Ligands of Formula 33 were used in the polymerization process.

2-hydroxyethyl-2'-methyl-2'bromopropionate was prepared as shown in Fig. 7.

The conditions used in steps (1) and (ii) was as follows:

0.25g of red phosphorous (8.06×10^{-3} mol) were added to 35.4 ml (0.338 mol) of isobutyryl chloride. The mixture was placed under gentle reflux and 20ml of bromine (0.338 mol) were added slowly over 8 hours. The mixture was refluxed for a further 4 hours and the crude reaction mixture added slowly to 350 ml of anhydrous ethylene glycol (6.27 mol). The reaction mixture was refluxed for 4 hours, filtered into 500 ml of distilled water and the product extracted into chloroform. After washing with water and sodium hydrogen carbonate and drying over magnesium sulfate the product was isolated as a colorless liquid after the removal of solvent and vacuum distillation at 64.5°C and 0.1 Torr. 'H NMR ($CDCl_3$, 373 K, 250.13 MHz) δ = 4.30 (t, J 9.6 Hz, 2H), 3.85 (t, J 9.6 Hz, 2H) 1.94 s, 6H), $_{13}$C ('H) NMR

($CDCl_3$, 373 K, 100.6 mHz) δ = 171.83, 67.30, 60.70, 55.72, 30.59, IR (NaCl, film) 3436 (Br), 2977, 1736 (s), 1464, 1391, 1372, 1278, 1168, 1112, 1080, 1023, 950, 644, El MS: 213, 211 (mass peaks), 169, 167, 151, 149, 123, 121. The typical polymerization procedure used (steps iii and iv) was as follows:

0.1376 of copper(1)bromide (98%, 9.6 x10^{-4} mol) were added to 40 ml of xylene and 20ml of methyl methacrylate (0.187 mol). 0.4272g of 2 (2.89 x 10^{-3} mol) were added and the mixture deoxygenated by one freeze-pump-thaw cycle prior to the addition of 0.2029g of 3 (9.61 x 10^{-4}) mol at room temperature. The deep red solution was heated at 90°C for 70 minutes. The final product was isolated by precipitation into hexanes.

Atom transfer radical polymerization of MMA using 3 as initiator in conjunction with 2 and CuBr was carried out at 90°C in xylene [MMA]:[3] = 20:1, [ligand]:[CuBr]:[3] = 3:1:1 to give PMMA of structure 4. Polymerization was stopped at low conversion, 7.65%, after 70 minutes, so as to reduce the amount of termination by radical-radical reactions, reaction A. 'H NMR data (Fig. 8), clearly shows the presence of the hydroxyethyl ester group, originating from 2 and the methoxy • to the bromo group at the propagating end at δ 4.28, 3.82 and 3.74 respectively. The number average molecular mass, Mn, can be calculated directly from NMR which gives a value of 2,430 which compares excellently with that obtained from size

exclusion chromatography against PMMA standards of 2,320, PDI = 1.12 (when precipitated into hexanes Mn - 2960, PDI = 1.12). This excellent agreement indicates that the product has structure 4. This is confirmed by matrix-assisted laser desorption-ionization time of flight mass spectrometry, Fig. 9. We see one series of peaks in the MALDI-TOF-MS indicating only one predominant structure i.e. 4. For example, the peaks at m/z 1319.0 and 1419.2 correspond to lithium adducts of 4 where x = 10 and 11 respectively, calculated m/z 1318.3 and 1418.4. The narrow PDI of 4 is indicative of k(propagation) > k(termination) i.e. pseudo living polymerization. Control over Mn and PDI is obviously not affected detrimentally by the presence of primary alcohol group present in the initiator, which might have been expected to complicate the reaction by coordination to the copper catalyst. Indeed the PDI is narrower and the rate of polymerization faster with 3 than that obtained using a non-functional initiator. This is currently under investigation. Thus, controlled polymerization with the copper complex as catalyst can be used to give PMMA or structure 4 as the only detectable product under these conditions. The hydroxy group can be further reacted with benzoyl chloride to give 5 quantitatively.

The terminal benzoyl group of 5 is observed by 'H NMR, Fig. 8(c) and is detected by SEC with UV detection at 200 nm, 4 shows no absorption at this wavelength. MALDI TOF shows a new series of peaks corresponding

to 5 e.g. peaks are now observed at m/z 1423.0 and 1522.8 for x = 10 and 11, calculated m/z 1422.3 and 1522.4; this reaction is quantitative and no peaks from residual 4 are observed. When the reaction is carried out at a higher [MMA]:[3] ratio for 120 minutes a higher molecular weight polymer is produced, Mn = 4540, PDI = 1.22, as expected, reactions B and C. Again analysis shows terminal hydroxy functionally.

Living or pseudo living polymerizations have a low rate of termination relative to rate of propagation. This is demonstrated by following a reaction with time, reactions D-K; L is the final product from this reaction. Fig. 10 shows that Mn increases linearly with conversion, up to approx. 80%, whilst PDI remains narrow for reaction with [MMA]:[3} - 200. In this case the expected Mn (theory) at 100% conversion = [100/1 x 100.14 (mass of MMA)] + 220 (mass of end groups) = 20248. The PDI is broader than would be expected for a true living polymerization with fast initiation (theoretically 1 + 1/DP). However, PDI does not increase with increasing conversion as would be expected for a reaction with significant termination and this is most probably due to slow initiation relative to propagation. 12

In summary, atom transfer polymerization with the copper complex as catalyst and 3 as initiator leads to •-hydroxy functional PMMA. The presence of the hydroxy group during the polymerization does not reduce the

control over the polymerization, and a narrow PDI polymer with controlled Mn is obtained. The reaction shows all the characteristics of a living/pseudo living polymerization. The structure of the product has been confirmed by MALDI-TOF-MS and NMR spectrometry. Furthermore the hydroxy functionality can be further functionalized by reaction with acid chlorides in a quantitative reaction.

Reaction[d]	[3]/ 10^4 mol	[MMA]/ mol	t/min	Conversion (%)[d]	Mn SEC	PDI SEC
A[b]	9.61	0.187	70	-	2530	1.10
B[c]	9.72	0.047	120	-	4540[e]	1.22[e]
C[c]	9.72	0.047	120	-	3130	1.22
D[b]	9.61	0.187	60	0.21	-	-
E[b]	9.61	0.187	120	2.27	-	-
F[b]	9.61	0.187	180	15.74	4980	1.21
G[b]	9.61	0.187	240	48.20	12330	1.26
H[b]	9.61	0.187	300	59.75	15580	1.29
I[b]	9.61	0.187	360	66.18	17920	1.27
J[b]	9.61	0.187	420	72.11	19500	1.27
K[b]	9.61	0.187	480	75.05	20100	1.28
L[b]	9.61	0.187	480	-	19427[e]	1.31[e]

[a] All reactions carried out with [2]:[CuBr]:[3] = 3:1:1. [b] 20 ml MMA in 40 ml xylene, [c] 5 mls MMA in 6 ml xylene. [d] From gravimetry. [e] After precipitation, otherwise as taken from reaction flask.

Further Examples of Initiators and Ligands

In order to demonstrate the effectiveness of the catalysts across the range of compounds chained, further experimentation was carried out.

Typical Polymerization procedure

Methyl methacrylate (Aldrich) and xylene (AR grade, Fischer Scientific) were purged with nitrogen for 2 hours prior to use. The initiator, ethyl-2-bromoisobutyrate (98% Aldrich), and CuBr (99.999%, Aldrich) were used as obtained and 2-pyridinal $^{n-}$ alkylimines were prepared as above. A typical reaction method follows. CuBr (0.134g, [Cu]:[Initiator]=1:1) was placed in a pre-dried Schlenk flask which was evacuated and then flushed with nitrogen three times. Methyl methacrylate (10ml) followed by 2-pyridinal $^{n-}$alkylimine ([ligand]:[Cu]=2:1) was added with stirring and, within a few seconds, a deep, brown solution formed. Xylene (20ml) and, if appropriate, inhibitor were then added and the flask heated in a thermostat controlled oil bath to 90^{o}C. When the solution had equilibrated ethyl-2-bromoisobutyrate (0.14ml, [Monomer]:[Initiator]=100:1) was added. Samples were taken by pipette at certain times or the reaction followed by automated dilatometry. This apparatus consists of a glass capillary tube that is set on top of a reaction vessel. The vessel is charged with a complete reaction mixture that has been freeze-pump-thaw degassed to ensure no dissolved gases are released into the capillary. After the vessel is fitted, the

capillary is filled with degassed solvent and the reaction mixture heated to the required temperature. During polymerization monomer is converted to polymer with a decrease in the volume of the mixture. This decrease in volume can be followed by watching the meniscus fall in the capillary, a process done in this case by an electronic eye controlled by a computer program.

Characterization of Polymers

Monomer conversion was calculated by gravimetry and/or ^1H NMR and the molecular weights and molecular weight distributions (polydispersities) found by get permeation chromatography using tetrahydrofuran as eluent and the following columns (Polymer Laboratories): 5μm guard and mixed-E (3000x7.5mm), calibrated with PL narrow molecular weight poly(methyl methacrylate) standards with differential refractive index detection and/or UV.

Exp.	Initiator Formula	Ligand Formula	Amount ligand/g	Solvent (conc wt%)	Amt. CuBr	Amt. Initiator/ mL	Temp. °C	Time mins.
1	15	28	0.375	50	0.134	0.181	90	210
2	15	28	0.375	50	0.134	0.181	90	360
3	15	29	0.37	100	0.134	0.156	40	1440
4	15	33	0.273	33.3	0.134	0.137	90	240
5	15	40	0.273	33.3	0.134	0.137	90	1200
6	15	39	0.273	33.3	0.134	0.137	90	1320
7	15	44	0.25	33.3	0.134	0.137	90	2580
8	15	46	0.600	33.3	0.134	0.137	90	2580
9	15	32	0.610	33.3	0.134	0.137	90	300
10	15	49	0.423	33.3	0.134	0.137	90	1200
11	15	29	0.494	33.3	0.134	0.137	88	290
12	15	29	0.494	33.3	0.134	0.137	88	1260
13	15	31	0.536	33.3	0.134	0.137	90	1137
14	15	41	0.590	50	0.134	0.130	90	120
15	15	42	0.590	50	0.134	0.130	90	120
16	15	41	0.590	50	0.134	0.130	90	240
17	15	47	0.42	50	0.13	0.14	40	1050
18	15	47	0.42	50	0.13	0.14	40	2505
19	15	34	0.358	36	0.134	0.137	90	150
20	15	35	0.386	36	0.134	0.137	90	150
21	15	36	0.414	36	0.134	0.137	90	150
22	15	37	0.442	36	0.134	0.137	90	150
23	15	38	0.70	36	0.134	0.137	90	150
24	21	28	0.37	33.3	0.13	0.16	90	300
25	21	33	0.41	50	0.13	0.16	90	120
26	22	33	0.41	33.3	0.13	0.52	90	240
27	21	33	0.41	33.3	0.13	0.08	90	240
28	21	33	0.41	33.3	0.13	0.05	90	240
29	21	32	0.37	100	0.134	0.156	40	1440
30	21	32	0.37	33.3	0.134	0.156	90	300
31	23	29	0.37	33.3	0.134	0.178	90	270
32	23	29	0.37	33.3	0.134	0.178	90	1320
33	16B	29	0.37	33.3	0.134	0.193	90	1320
34	16B	45	0.45g	50	0.13	0.19	90	2760
35	23	45	0.45g	50	0.13	0.19	90	2760
36	16B	29	0.185	33.3*	0.067	0.096	90	2880

* 25 mL of MMA

Results

Exp.	Mn	PDI	%Conversion
1	10818	1.28	100
2	5060	1.34	13.5
3	12310	1.70	91.6
4	9198	1.19	66
5	8717	1.49	87
6	31666	1.65	49
7	9054	2.71	2
8	5250	1.63	2
9	21318	1.78	86
10	53395	1.72	39
11	8990	1.16	55.6
12	15147	1.26	97.6
13	8710	1.36	47.1
14	4300	1.45	5
15	4700	1.65	10
16	6200	1.45	28
17	6577	1.27	47
18	11216	1.23	75
19	6500	1.18	60.0
20	7400	1.20	68.3
21	7320	1.20	72.1
22	7580	1.20	73.4
23	7900	1.23	73.4
24	11710	1.30	
25	28314	1.19	
26	7700	1.14	
27	28330	1.15	68.5
28	36380	1.17,	50.6
29	23780	1.07	38.5
30	26640	1.17	52.52
31	2177 2135 (by NMR)	1.10	
32	1000	1.11	3.8
33	1900	1.08	20.3
34	11009	1.08	
35	10200	1.13	
36	23700	1.13	